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GEOLOGICAL INVESTIGATIONS RELEVANT TO EARTHQUAKE ENGINEERING PROBLEMS

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Virtually all large earthquakes are caused by sudden movements on faults, which are simply surfaces of shearing within the earth's crust. We know this not only from the observations of surface faulting during large earthquakes, but also from seismological studies indicating that the source mechanism of large earthquakes is indeed an abrupt shearing process and not some other sort of mechanical phenomenon such as implosion or tensile failure. The energy released during large earthquakes demands fault ruptures of significant lengths, with rupture lengths of up to 1000 km being observed during the largest of earthquakes; even a relatively moderate earthquake of magnitude 6 normally requires a fault rupture length of 5-10 km. The largest fault displacements observed at the ground surface during individual historic earthquakes are 11.5 m vertical (Assam, 1897) and 9.9 m horizontal (Mongolia, 1957), although significantly larger individual fault displacements at depth are inferred from some geodetic observations.

Thus the study of faults by geologists and seismologists is critical to the understanding of where earthquakes are likely to occur, how big they are likely to be, and how often they are likely to take place. A principal effort at the present time is to quantify the answers to these questions, at least in a probabilistic sense, in order to allow engineers to make wise decisions as to the siting and earthquake-resistant design of structures.

Most large, shallow earthquakes--the ones of principal concern to engineers--occur on faults that extend to the ground surface and can thus be identified and studied by geologists. Furthermore, virtually all large earthquakes worldwide have occurred on faults that have had a previous history of earthquake displacements within the recent geologic past--usually within the past few tens of thousands of years. Thus if the geologist can determine how often a given fault has moved during the recent past, he or she can make probabilistic estimates of how likely it is to rupture in an earthquake during a specified time interval in the near future. It is important to recognize this observational basis of hazard evaluation: virtually all large earthquakes have occurred on faults that had been, could have been, or should have been recognized and studied by geologists prior to the event. One might well ask how a new fault is ever "born" if all large earthquakes occur on pre-existing faults, but it seems that long faults grow from the gradual lengthening and coalescing of smaller faults over millions of years, so that a truly great fault such as the San Andreas was not "born" during a single massive earthquake in the distant past. Nor, of course, is this likely to occur in the future.

There are some notable exceptions to the direct correlation between large earthquakes and faults that can be identified at the earth's surface, and these exceptions constitute a major problem for the geologist. Although, as stated above, virtually all large earthquakes indeed occur because of movements on faults, in some cases, such as that represented by the damaging Charleston, South Carolina earthquakes of 1886, the causative fault does not seem to be exposed at the ground surface. Geophysical investigations thus become relatively more important in these situations, most of which occur in areas of relatively low seismicity far from active plate boundaries. Fortunately, these instances are relatively rare on a worldwide basis, but they constitute a major challenge to the geologist and geophysicist in attempting to evaluate seismic hazard in areas such as the eastern United States and parts of southern Europe.

In identifying seismogenic faults, the geologist must use a number of techniques in order to determine how recently and how often a fault has moved in the recent geologic past. The physiographic expression of a fault resulting from recent displacements can be an important clue, because the relief of the earth's surface is ephemeral, and the topography caused by surficial fault displacements tends to be modified and erased very rapidly. Thus "fresh" fault scarps are indicative of a high degree of fault activity, although faults with different senses of displacement (e.g., vertical vs. horizontal) have differing types of geomorphic expression that must be carefully evaluated by the geologist. History has shown that thrust faults--those with one block overriding the other on a shallowly inclined fault plane--are particularly difficult to recognize and evaluate in the field, yet such faults have been the culprits in a large proportion of the world's truly great earthquakes.

In the past, there has been a tendency to classify faults as either "active" or "inactive," depending on whether they have moved within a specific period in the past; an "active" fault was considered "dangerous," and an "inactive" fault was considered "safe." We now recognize that such a distinction is a bit naive, inasmuch as there appears to be a complete continuum of faults from those of a very high degree of activity to those of a very low but still finite degree of activity. A highly active fault, such as the great thrust fault marking the subduction zone beneath southern Chile, may generate a great earthquake on the average of once every 100 years, whereas other major faults may have a recurrence interval between major earthquakes of more than 10,000 years. Both might be considered "dangerous," but with widely varying degrees of hazard. The challenge of the geologist is to attempt to quantify these differences, and thus the degree of hazard.

The most exciting recent improvement in the geologic understanding of seismogenic faults is the development of field techniques for determining the dates of individual prehistoric earthquakes on a given fault--a field that has been termed "paleoseismology." It is based on the absolute age determination, usually by Carbon-14 methods, of buried strata that immediately predate and postdate a "fossil earthquake" that can be identified by structural relationships--usually in the wall of a trench excavated across the trench. Among the features that have been used to identify individual paleo-earthquakes on trench walls are these:

(1) Identification of a fault that can be shown to break older strata but which is in turn erosionally truncated and buried by unbroken younger strata that had not yet been deposited at the time of the earthquake, thus bracketing the time interval within which the earthquake must have occurred.

(2) Identification of buried sand-blow deposits resulting from soil liquefaction during heavy shaking, usually close to or along the causative fault.

(3) Identification of a fault scarp that was subsequently buried by younger unbroken deposits.

(4) Closely related to (3), identification of a buried landslide feature or a colluvial apron derived from a fresh, eroding fault scarp.

(5) Identification of a crevice associated with surficial fault movement, that was later filled in by surficial materials.

Although each of the above techniques applies ideally to a single paleo-earthquake, a number of repeated earthquakes are likely to be represented in a single exposure, so that the resulting geological relationships can become very complex; relationships resulting from one earthquake are modified by subsequent earthquakes along the same fault. Trenches only 5 m deep across the San Andreas fault in southern California, for example, reveal evidence of 12 individual great earthquakes on the fault within the past 2,000 years.

In all of these paleoseismological techniques, optimal bracketing of the time of the earthquake requires dating of (1) the oldest unbroken post-earthquake strata, and (2) the youngest deformed pre-earthquake strata. Unfortunately, the probability is small of this being practical in any individual exposure. That is, the chances are slim of finding a locality where one of these unique geologic situations can be observed, and where the adjacent rocks can be radiometrically or otherwise dated. Nevertheless, for those investigations that have been successful, such as along the San Andreas fault of California, the Wasatch fault of Utah, and the Red River fault of China, the results have been profound in terms of seismic-hazard evaluation. For the first time we have a chronology of earthquakes in the recent past, and thus a firm basis for probabilistic estimates of future events.